HANDBOOK OF PLASMA IMMERSION ION IMPLANTATION AND DEPOSITION

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Edited by

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PREFACE

Plasma processing of materials has matured in recent decades at an incredible speed. Conventional techniques have been upscaled, in situ monitoring and computer-aided feedback controls have become standard, and new processing methods have been invented. The turn of the millennium is a welcome occasion to step back for a moment from the fast pace of day-to-day operation of research, development, and high-tech production. Before we ‘‘immerse’’ ourselves into technology details, let’s step back and have a look at the big picture. Materials research and development is a cornerstone of modern industry; it provides enabling technologies for the information age. There would be no high-speed computing, wide bandwidth network connections, wireless communication, and the like without modern materials technologies. Innovative process solutions and materials are also developed for the more traditional areas in manufacturing and transportation, including the space and automotive industry. At the same time, scientists, engineers, and economists are today more aware than ever of the environmental impact of modern technologies. In fact, the need to replace technologies that have severe negative environmental impact has become a major driving force for the development of better alternatives.

One of the emerging technologies is plasma immersion ion implantation (PIII), also known as plasma source ion implantation (PSII) or plasma-based ion implantation (PBII). In order to appreciate PIII, we will start with a quick comparison with conventional beamline ion implantation. Energetic ion beams are obtained from ion beam sources by extracting ions from a plasma and accelerating them using the electric field across a single or multiple aperture grid system. The electric potential difference between the grids is high: often tens or hundreds of kilovolts, and sometimes the ion energy is further increased to the mega-electron-volt range utilizing accelerator stages. The ion beam cross section is usually small (compared to the substrate area), with three important consequences: (1) feasibility of magnetic ion charge and mass separation, (2) the need for scanning the beam across the surface area to obtain large implantation areas with sufficient dose uniformity, and (3) low dose rates and long processing times. PIII, in contrast, is a very different approach that leads to opposite features. The substrate to be implanted is immersed in the processing plasma, and negative high-voltage pulses are applied so as to form a conformal electric sheath (space charge layer) between the substrate and the plasma. Ions located in or entering the sheath from the plasma side are accelerated by the sheath's electric field. They are implanted into the substrate when they impact the substrate. The fascinating idea of this approach is to eliminate the need for ion beam extraction, focusing, transport, scanning, and other manipulation. These are some of the advantages of PIII. Other features, including drawbacks and limitations, will be discussed in detail in this handbook.

Plasma calculations by Melvin Widner at Oak Ridge National Laboratory in the 1960s and the pioneering work of Richard Adler at Mission Research Corporation in the early 1980s prepared the field. However, it was the work of John Conrad and co-workers at the University of Wisconsin at Madison that was pivotal for the birth and recognition of the PIII concept. They reported on the first plasma immersion ion implantation results with nitrogen plasmas in 1986. Nitrogen plasmas were dominant in the early years because one could form subsurface nitrides at relatively low temperatures with excellent mechanical and chemical properties. In the following years, the physical basis has been developed by a number of groups, and new applications have been explored. I'm grateful that John agreed to write the first chapter of this handbook, describing the early development of PIII and its relation to other techniques, in particular to ion nitriding. He puts the development of PIII&D in a historical perspective by comparing it with traditional beamline ion implantation. He outlines the physics and original applications of PIII.

The early PIII work used gaseous plasmas such as nitrogen plasmas. By extending PIII to condensable (metal or organometallic) plasmas and vapors, the field was expanded from pure ion implantation to thin-film deposition. As a consequence, the letter *D* for deposition was included in the acronym, now PIII&D. The title of this handbook, plasma immersion ion implantation *and deposition*, reflects this development.

If condensable plasma species such as metal ions are involved, this concept translates into ion implantation and ion deposition phases. Pulsing the substrate implies high-energy phases (bias pulse on, ion implantation) and low-energy phases (bias pulse off, ion deposition). Figure 1 illustrates the hybrid character of PIII&D. In general, PIII&D equipment and processes may be operated in a pure plasma immersion ion implantation (PIII) mode or a pure plasma immersion ion deposition (PIID) mode (the latter has existed before PIII was invented, as pointed out in Chapter 1). The following acronyms are used in this book: PIII for plasma immersion ion implantation with gaseous plasmas, PIIID for plasma immersion ion implantation and deposition with condensable, film-forming plasmas and vapors, and PIII&D when generically referring to both.

Today, at the turn of the millennium, PIII&D in its various forms has become a mature technology with first applications of industrial size. Our knowledge has been compiled and described in several book chapters, and about 1000 articles have been published in a variety of scientific journals.

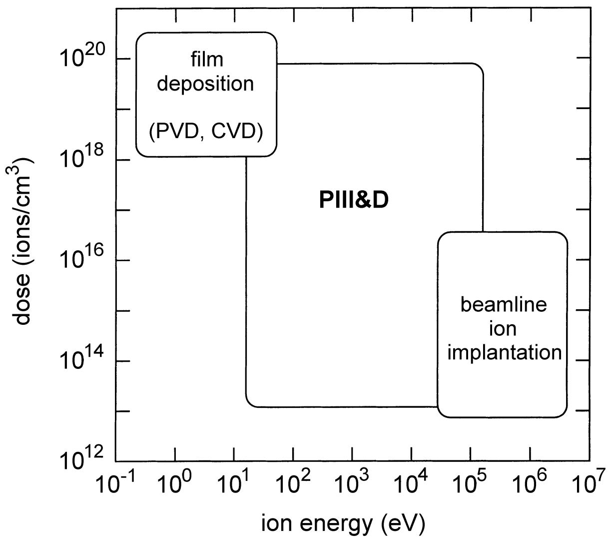

Figure 1 Relation of PIII&D to ion implantation and thin-film deposition.

Several International Workshops on Plasma-Based Ion Implantation have demonstrated the vitality of the field. The time has come to consolidate the work in a single monograph dedicated to this field; this handbook describes the PIII&D work from its beginnings to the end of the twentieth century.

Plasma physicists, materials scientists, chemists, pulse-power engineers, and many others have contributed to the development of PIII&D, a field at the interface of several scientific disciplines. It seemed mandatory to include a rather large number of authors and draw from their different and complementary experience and expertise.

This book is composed of three parts: *Fundamentals, Technology*, and *Applications*. In Part I, the basics of plasmas and plasma sheaths are introduced by Michael Lieberman. Background information on ion implantation and thin-film formation is provided in Chapter 3, coordinated by Michael Nastasi. In Chapter 4, the fundamental processes of PIII and their extension to PIIID are introduced by Blake Wood and co-authors. This chapter is the core of the handbook; it is not coincidental that its title is practically identical with the title of the Handbook. If you are familiar with the basics of plasmas, sheaths, ion implantation and thin-film deposition, and you would like to learn about PIII&D, I would recommend that you go straight to Chapter 4. Chapter 5, coordinated by Kevin Walter, gives an overview of materials analysis and testing techniques. This chapter will be found useful by those who want to be reminded of the various methods for determining the qualitative and quantitative effects of PIII&D treatment. Of course, all of the chapters contain numerous references that allow the reader to probe deeper in the original literature. Chapter 5 concludes the fundamentals part of this handbook.

In Part II, Jesse Matossian and co-authors discuss design issues of PIII&D processing chambers, process control, part handling, and other information relevant to the practical design and use of PIII&D vacuum equipment. In Chapter 7, coordinated by myself, plasma sources and the technical means of plasma production and control are discussed. Chapter 8, coordinated by Dan Goebel, deals with the pulser technology necessary to achieve suitable substrate bias pulses. The *Technology* part is concluded by Chapter 9, coordinated by Dexter Beals, in which safety and health issues are discussed that are related to the variety of PIII&D processes.

Part III starts with nonsemiconductor applications such as the reduction of wear and corrosion of PIII-treated workpieces, the core application of PIII in its early years. Chapter 10, coordinated by Kumar Sridharan, also includes applications of PIIID such as the deposition of compound layers and fine-tuned hard amorphous (diamondlike) carbon films. Finally, Chapter 11, coordinated by Paul Chu, describes modern applications in semiconductor research and industry such as the PIII formation of ultrashallow junctions.

Twenty-nine distinguished authors from six countries have contributed to this book. I feel privileged that I had the opportunity to work with them and that I was given the honor of coordinating and editing this handbook. The authors are portrayed in short biographies compiled in Appendix D.

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